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THE MANUFACTURE OF CADMIUM SULFIDE THIN FILM SOLAR CELLS AT THE RATES OF 1 KILOWATT PER MONTH AND 5 KILOWATTS PER MONTH

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FEASIBILITY STUDY

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SUMMARY

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This study determined the manpower, materials and additional facilities necessary to produce the cadmium sulfide (CdS) thin film solar cell in the present state of the art at the rates of 1 kilowatt and 5 kilowatts per month. Four courses of action were checked in some detail. The study indicated that reduced equipment costs and a long-term saving in space and labor could be achieved by choosing that course of action involving a modest amount of development of advanced equipment.

author

INTRODUCTION

The problem of determining the additional facilities, etc., necessary to produce the cadmium sulfide (CdS) thin film solar cell at the rates of 1 kilowatt and 5 kilowatts per month was attacked in the following manner.

First, all of the essential steps in the fabrication of the cell were outlined in the form of a flow chart (Figure 11a, b) showing the sequence of operations and the operations that could be performed simultaneously.

Next, an estimate was made of the yeilds to be expected for each operation based on actual experience. Actual use production rates and projected rates for the individual equipment items were established. Then calculations were made starting with the required monthly kilowatt yields and working back toward the starting materials to establish the through-put required for each operation. Knowing this, it was possible to determine the equipment quantities required to sustain each operation. At this point the study begins to assume larger proportions.

It was deemed advisable to consider the present laboratory equipment types and sizes for the initial study of the 1 kw per month phase since there was a distinct possibility that only an increase in the quantity of certain pieces of equipment was needed. This was found to be true, but with certain qualifications. The 5 kw per month study could also be essentially a scale up by a factor of 5 but, as will be seen later, would not be too advisable.

The information on the present types of equipment was readily available, but some equipment required design revision. This was accomplished by interhouse discussion and designing, plus discussions with suitable outside firms on an inquiry basis. Such inquiries have been found necessary only in the evaporation equipment area. For example, a quick change evaporation source and a clamp-type substrate heater holder would save operator time for the double evaporator and five-station units. As another example, a continuous, fully automatic system was investigated but found to be far too expensive.

At each stage of the operation, a determination was made with respect to the labor requirements. In order to ascertain the best balance between labor and equipment, the maximum labor and minimum equipment was compared with maximum equipment and minimum labor. Optimization was made based on what was considered to be necessary to insure the production of a quality product at lowest cost.

This analysis procedure permitted the formulation of plans for production schedules.

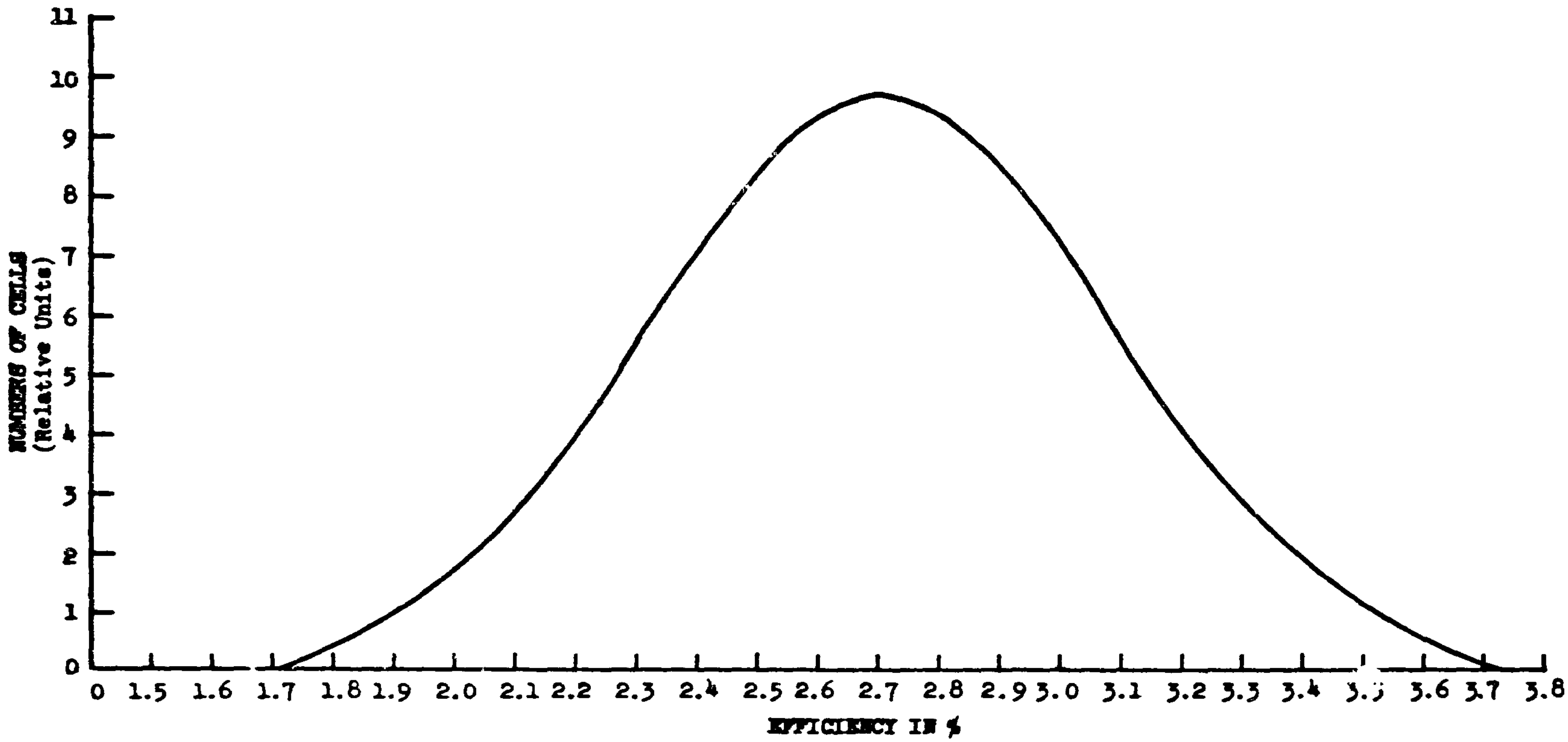
Analysis Of The 1 Kilowatt Per Month Requirement

A cell (7 cm x 7 cm) of suitable quality converts approximately 1/8 watt. (See Fig. 1). Then a production rate of 1000 watts per month by present laboratory equipment types would correspond to 8000 acceptable cells per month. (See Fig. 2). Assuming a net yield for initial inspection and test, lay-up and electroding, lamination and final inspection and test, of 90%, then 8861 sheared cells (7 cm x 7 cm) per month would be needed. At a yield of 97% for shearing, approximately 2332 nominal 6" x 6" cells would be required (one 6" x 6" corresponds to four 7 cm x 7 cm cells). Approximately 1/2% of cells are lost in the wiping process so that 2343 oxidized cells would be needed. Nearly 5% of cells show up defects during oxidizing so that 2468 plated and rinsed cells would be required. Approximately 10% of cells are lost during plating and rinsing so that 2743 evaporated films would be needed. The yield for the evaporation process is approximately 99% so that 2771 evaporations should be performed. Approximately 2% of the substrates are lost in the cleaning and etching process so that 2827 unetched 6" x 6" substrates would be required each month.

Assuming the above requirements, and 20 working days per month with 3 shifts per day, an estimate can be made of the manpower and equipment necessary. (See Tables 1 & 2, and Fig. 3). Approximately .05 man per shift will be needed to trim molybdenum substrates on a three shift basis. .20 man per shift will be needed for substrate cleaning. .10 man per shift will be needed for acid etching, rinsing, inspection and storage. .5 man per shift will be needed to prepare loaded evaporation sources. The substrate can be trimmed by the same man and shear used to shear the cells. Other substrate preparation and evaporation source preparation will be done by one man. He will need an ultrasonic cleaner, some glassware and various hand instruments. A double evaporator will produce 7 or 8, 6" x 6" films per shift. Assuming three shifts per day and an average of 20 days per month, approximately six double bell jar units and one operator per shift will be needed, mounting films for plating will require .48 man per shift. Plating will require .57 man per shift.

Figure 1

TYPICAL DISTRIBUTION CURVE FOR
CdS PILOT PRODUCTION



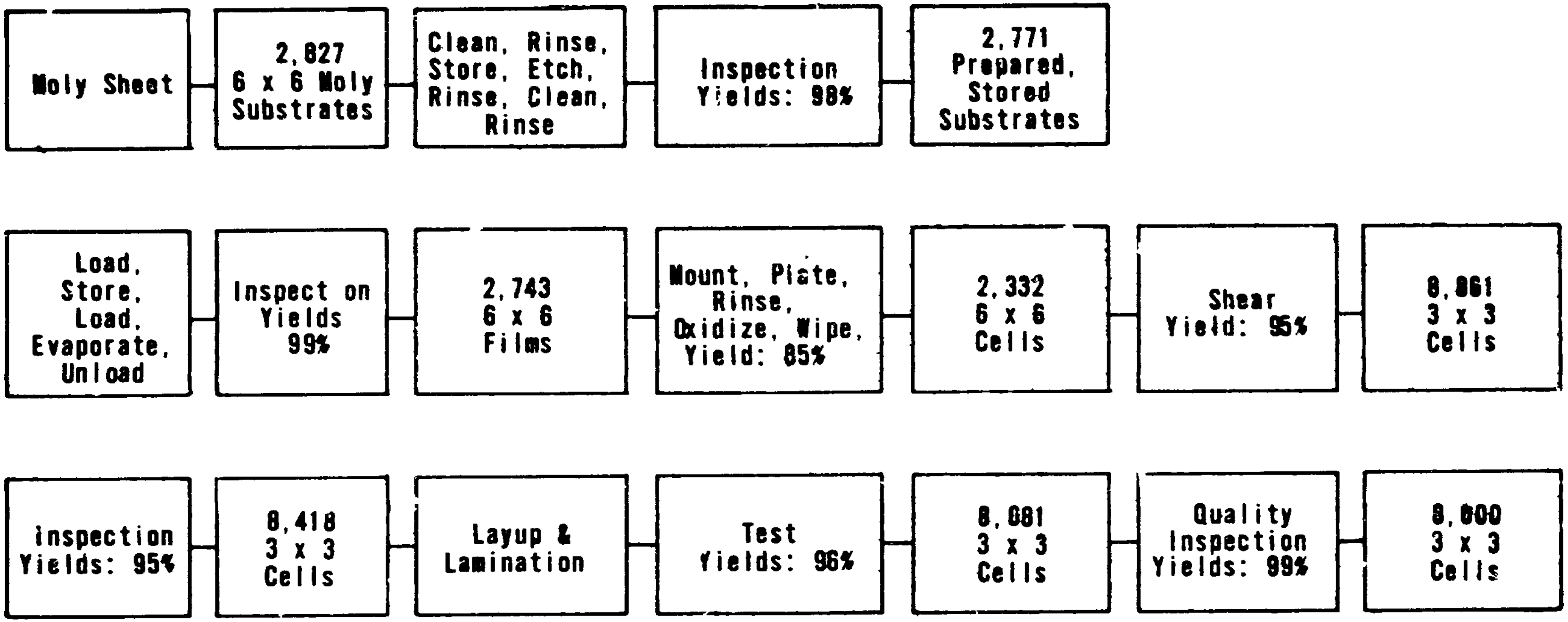


Figure 2

Yield Factors and Cell Quantities for 1 KW/Month

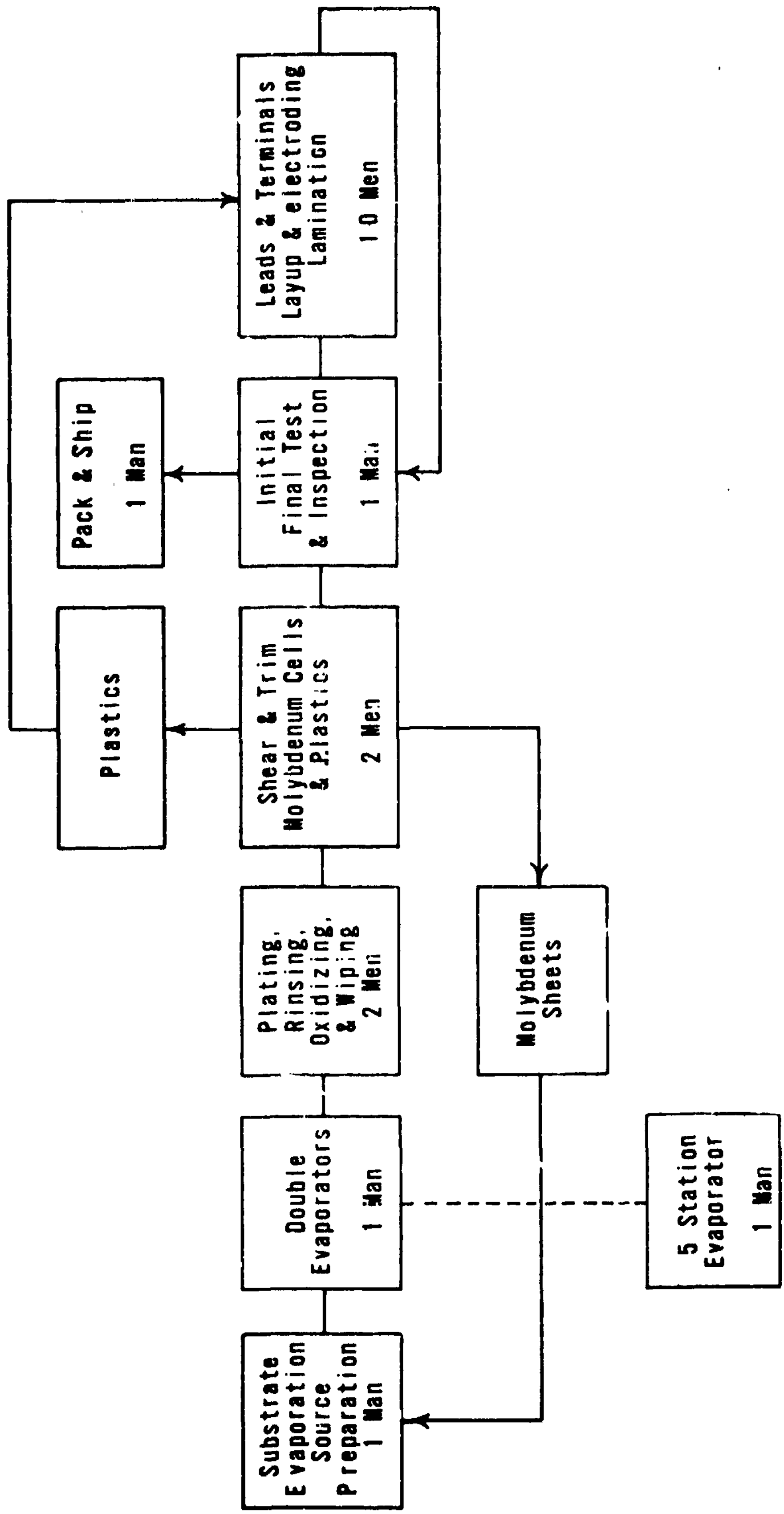

Substrate Evaporation Source Preparation 1 Man
Double Evaporators 1 Man
5 Station Evaporator 1 Man
Plating, Rinsing, Oxidizing, & Wiping 2 Men
Molybdenum Sheets
Shear & Trim Molybdenum Cells & Plastics 2 Men
Plastics
Initial Final Test & Inspection 1 Man
Pack & Ship 1 Man
Leads & Terminals Layup & electroding Lamination 10 Men

Figure 3

TABLE 1

MANPOWER FOR 1 KW/MONTH

(1) DOUBLE EVAPORATORS: (20 DAYS/MONTH), (24 HOURS/DAY)

Operation	Number /Month (6x6)	Number /Day (6x6)	Time /Unit (minutes)	Time /Month (hours)	Time /Day (hours)
Shear & Trim	2827	141	.5	23.6	1.18
Clean	2827	141	2.	94.4	4.72
Etch	2827	141	1.	47.2	2.36
Load Boats	2771	139	5.	231.	12.6
Evap.	2771	139	10.	462.	23.1
Mount	2743	137	5.	229.	11.5
Plate	2743	137	6.	275.	13.75
Rinse	2743	137	1.	45.8	2.30
Oxidize	2468	123	.5	20.6	1.03
Wipe	2343	117	5.	196.	9.8
Shear & Trim	2332	117	15.	584.	29.2
Inspect & Test	8861(3x3)	443(3x3)	2.	296.	14.8
Leads & Terminals	8418	421	5.	702.	35.1
Layup & Elect.	8418	421	25.	3510.	176.
Lam.	8418	421	5.	702.	35.1
Test	8418	421	1.	140.	7.0
Quality Inspection	8080	404	1.	135.	6.7
Label	8000	400	1.	133.	6.7
Pack & Ship	8000	400	4.	533.	26.7

(2) ADVANCED 1 KW/MONTH METHODS: (20 DAYS/MONTH), (24 HOUR/DAY)

Load Boats	2771	139	5.	231.	12.6
Evap.	2771	139	5.	231.	12.6

Other operation times same as above in Section (1).

TABLE 2

EQUIPMENT NEEDS FOR 1 KW/MONTH		METHOD A (PRESENT EQUIPMENT)		
Item	Type	Unit Cost	No. Required	Total Cost
Metal Shear	Di-Arco No. 3	$ 345	1	$ 345
Ultrasonic Cleaner	Westinghouse MT-1	1,200	1	1,200
Evaporators	Kinney Double Bell Jar	12,000	6	72,000
Thickness Monitor	Federal Products Air Gage	345	1	345
Plating	Harshaw D. C. Power Supply	200	1	200
Rinsing	Barnstead Transistor Washer TW 50	5,200	1	5,200
Oxidizing	Fries Oven No. 605	725	1	725
	Lectrodryer Air Dryer R-6	630	1	630
Initial Test	Harshaw Pressure Unit, etc.	750	1	750
	Tektronix Scope (Use also on Final Test)	500	1	500
Lamination	Pasadena Hydraulic Inc. Press and Plattens	830	2 sets	1,660
	Welch Vacuum Pump 1402B	255	2	510
	Tooling	350	2 sets	700

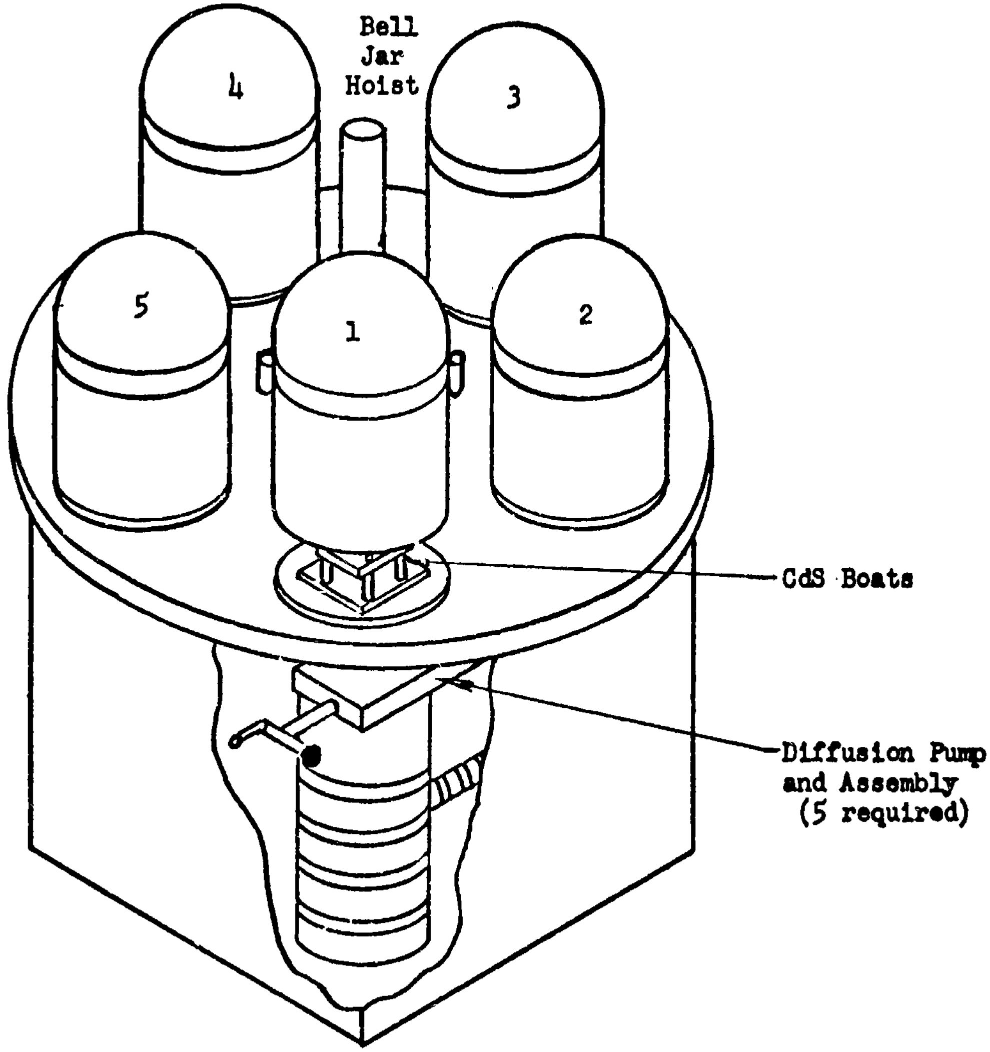
EQUIPMENT NEEDS FOR 1 KW/MONTH (Same as above except for the evaporators)	METHOD B (MODIFIED EVAPORATOR)		
5 Station Evaporator	35,000	1	35,000

Rinsing will require only .10 man per shift. .04 man per shift will be needed to oxidize the cells and .41 man per shift will be needed to wipe them. Probably one man per shift can handle plating, rinsing, oxidizing and wiping.

Shearing will require 1.22 men per shift. Initial inspection and power output test will require .5 man per shift. Preparation of leads and terminals will require 1.5 men per shift. 7.3 men per shift will be needed for lay up and electroding. Lamination will require 1.5 men per shift. .5 man per shift will be needed for final inspection and testing. Probably ten men per shift will be needed for leads and terminals, lay up and electroding, and lamination. They will need one metal shear, two presses with associated equipment and numerous smaller instruments. Initial and final inspections and tests can be done by one man per shift equipped with a special pressure test unit and an oscilloscope.

1 KW/Month - Advanced Equipment

To reduce space and labor requirements, a five station evaporator has been designed which utilizes fully the present knowledge of CdS solar cell manufacture. (See Fig 4). Each station (see Fig. 5) contains the same types of substrate heater and holder, transformer, sources, holding pump, trap and diffusion pump as half of a double evaporator. This method would, therefore, require no change in basic technique of evaporation. One roughing pump would be used. The five stations would be cycled through five phases by one operator. Each phase would be 20 minutes in length. At the first station, a vacuum cleaner would remove loose CdS accumulated during the previous evaporation. Then two substrates and the evaporation sources would be loaded into the chamber. At the same time, the chamber of the second station would be pumped down while the substrate is heated up. The evaporation of the first film would be in progress at the third station. The substrate holder flips over and a second set of boats in the evaporation source heats to full temperature at the fourth station. (Refer to Figures 6 and 7). The substrate, film, and evaporation source cool down at the fifth station. At the end of the 20-minute period, the completed CdS film and empty evaporation sources are unloaded from the fifth station and replaced with a fresh substrate and filled evaporation sources. As can be seen from the production schedule, (Fig.11a,b), there would be a reduction in the number of chambers from 12 to 5 compared to the double evaporator method. This would mean a reduction in space, and as can be seen from the equipment list (Table 2), a reduction in equipment cost.



(1) Load & Unload
(2) Pump down & Degassing
(3) Evaporation (Heating of Boats)
(4) Evaporation (Heating of Boats)
(5) Cooling

Figure 4

Pictorial Sketch of Evaporator for Advanced 1 KW/Month

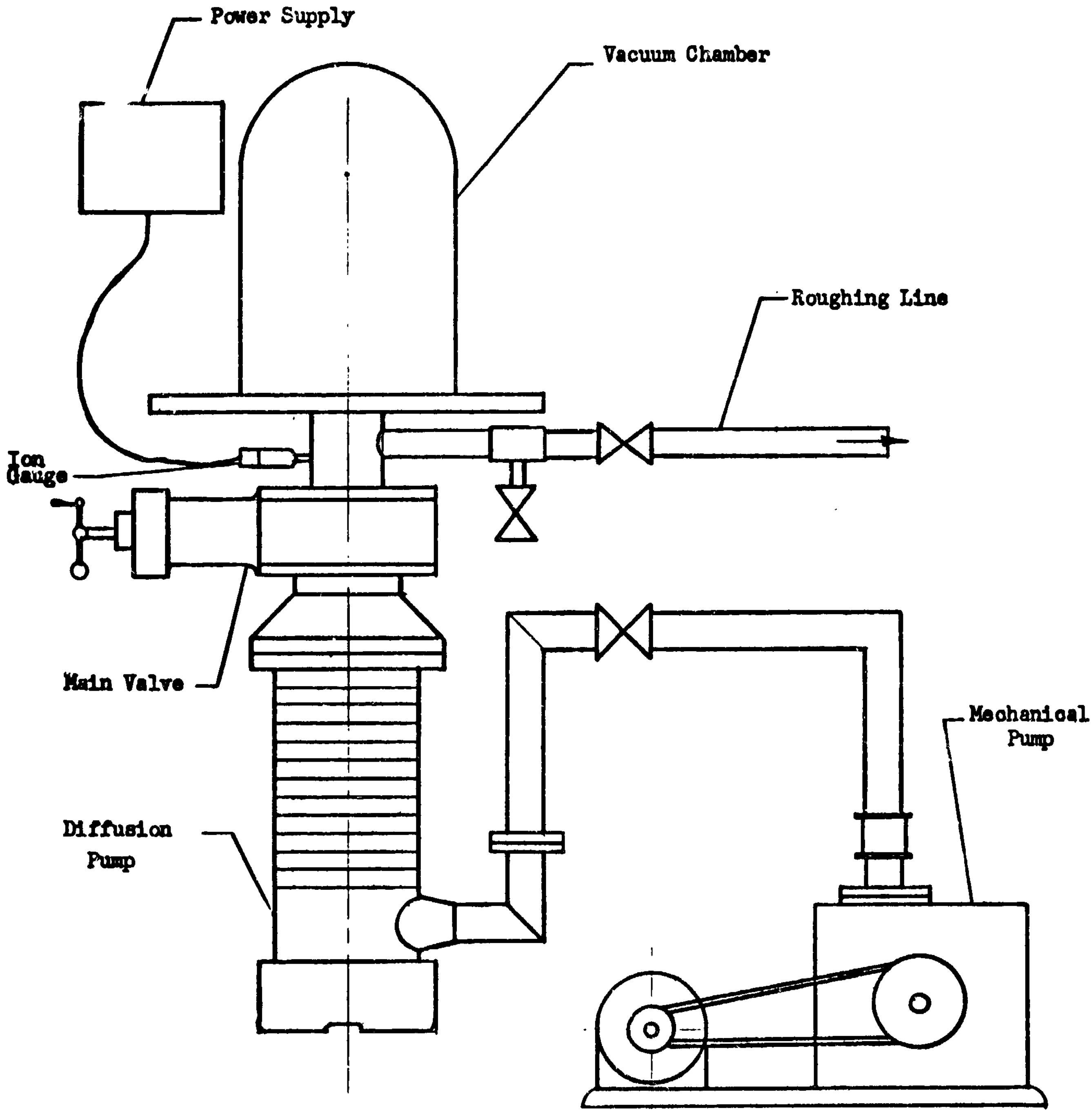
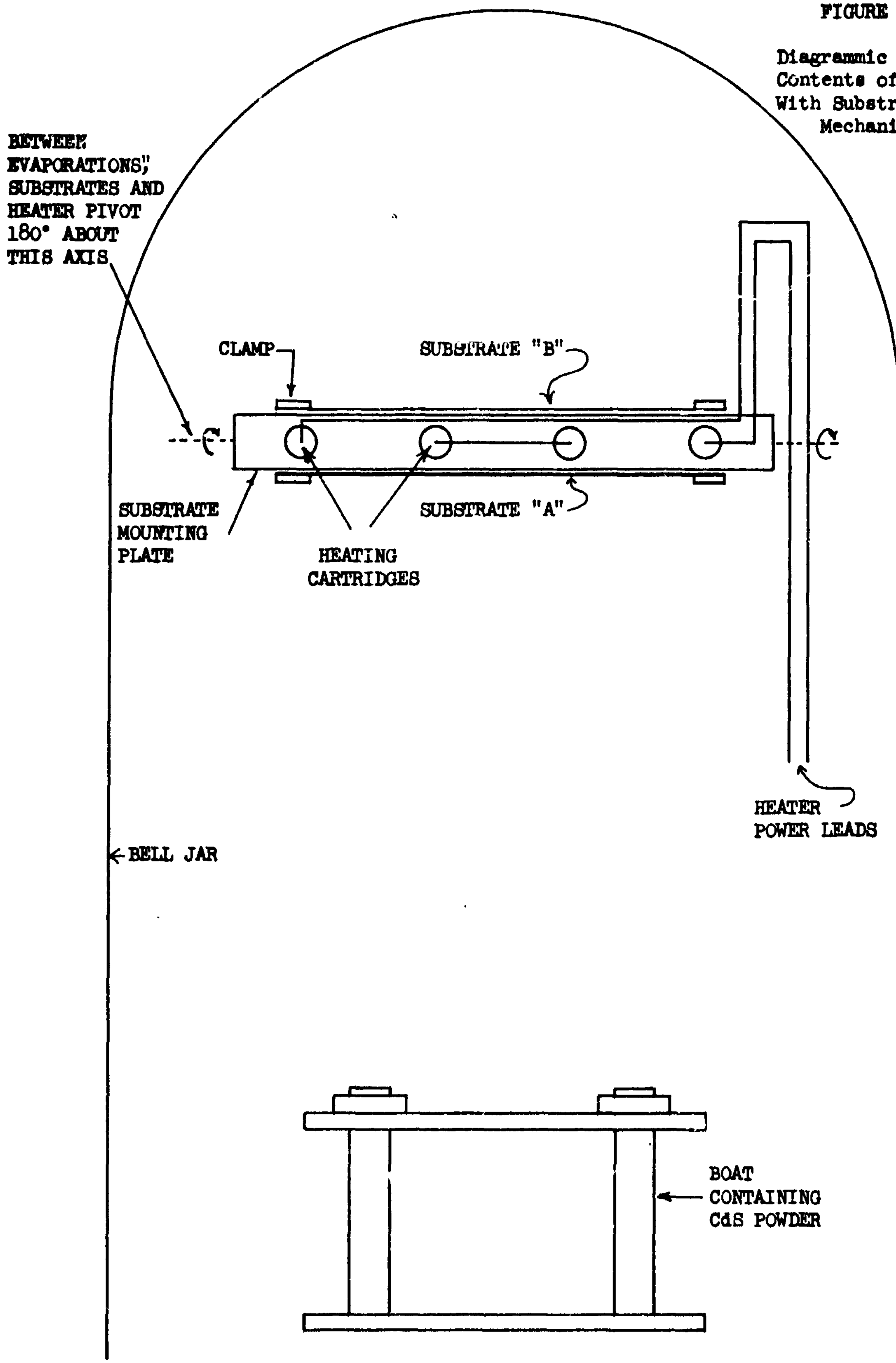


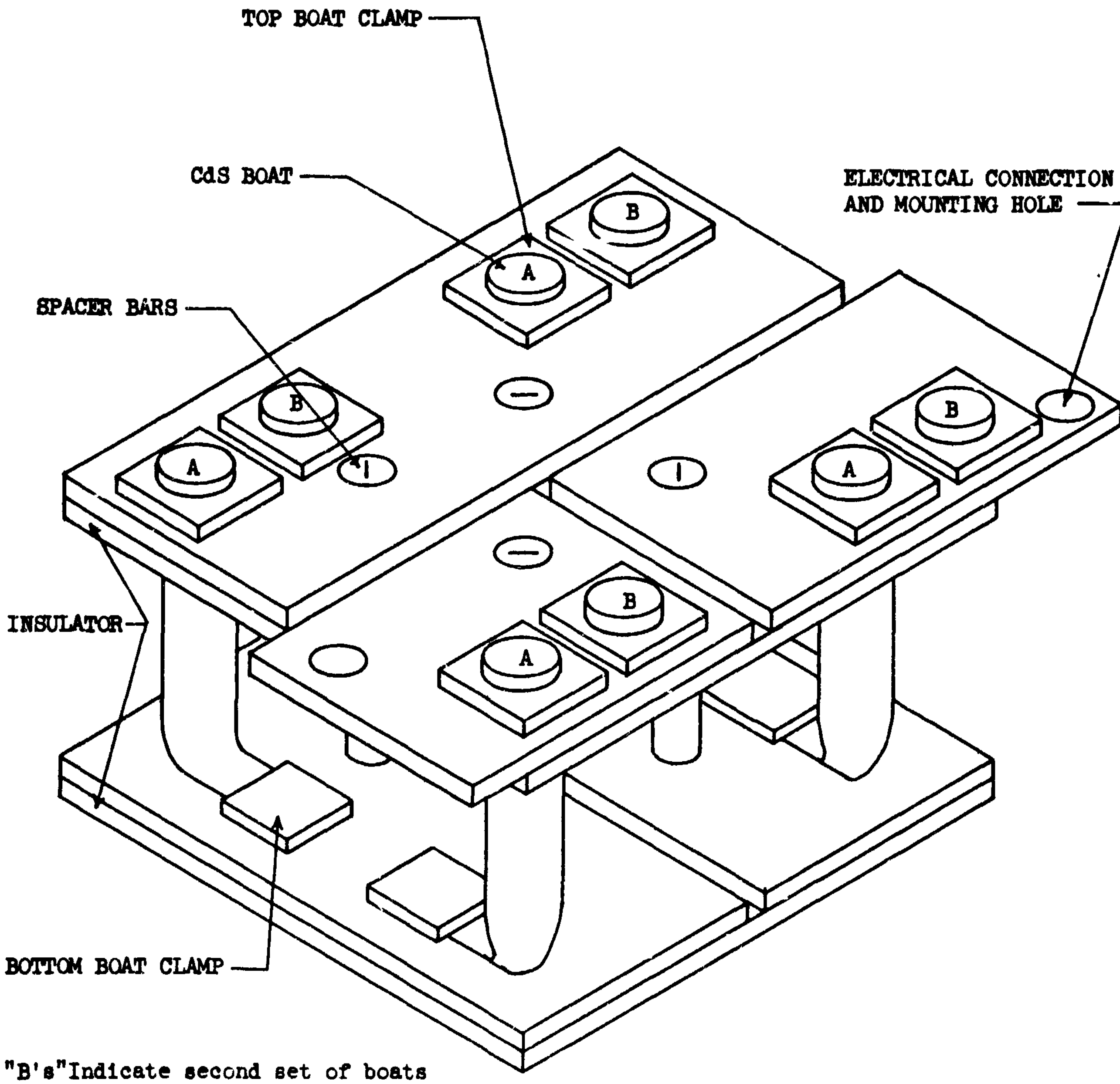
Figure 5

Diagram of One Sta ion of the Evaporator for Advanced 1 KW/Month

FIGURE 6

Diagrammic Sketch of Contents of Bell Jar With Substrate Rotating Mechanism





"B's"Indicate second set of boats

"A's"Fire together

"B's"Fier together

Figure 7

Evaporation Sources

Analysis of 5 KW/Month Based On Advanced 1 KW/Month Types

To obtain an output of 5 KW/month, 40,000 acceptable cells (7 cm x 7 cm) would be needed. (See Table 3 and Fig. 8). Correspondingly, 44,302 cells should go from shearing to initial testing. Approximately 11,658 nominal 6" x 6" cells would be needed for shearing. 11,715 oxidized cells would be required. 12,340 plated and rinsed cells should go to the oxidizing oven. 13,716 evaporated films would be needed. 13,854 evaporations should be performed. 14,137 unetched nominal 6" x 6" substrates would be needed each month.

5KW/Month Based On Advanced 1 KW/Month Types

A production rate of 5 KW/month would require 31 double evaporators. Then cost would be approximately $372,000. An operating area of 3,350 sq. ft. would be needed. Five operators would be needed. As can be seen from Table 2, only 5 five-station evaporators would be needed at an estimated total cost of $175,000. An operating area of 720 sq. ft. would be needed. Three operators would be needed. It is seen, then, that the five-station evaporators are much more practical for 5 KW/month than the double evaporators.

Plating would be done in a tank type unit. Multiple cell racks would be used. The cell holders in the rack would have a gasketed, mechanical stop-off feature which would be more reliable than stop-off taping and would require less labor. Stop-off taping requires approximately 5 minutes for a 6" x 6", where the improved cell holders would reduce mounting time to less than half a minute. Multiple rack plating should give an average plating time of .75 minute per 6" x 6". Because cells should not be stored between the steps of the barrier forming process, 1 KW/month probably could not make use of this labor-saving equipment.

Details of the equipment requirements for a rate of 5 KW/month, based on advanced 1 KW/month methods, will be found in Table 4.

5 KW/Month-Advanced Equipment

The 5 KW/month rate of production requires a departure from the present methods of manufacture with respect to the formation of the CdS films. The nearly handcrafted procedure will not suffice because of equipment, space, requirement and labor.

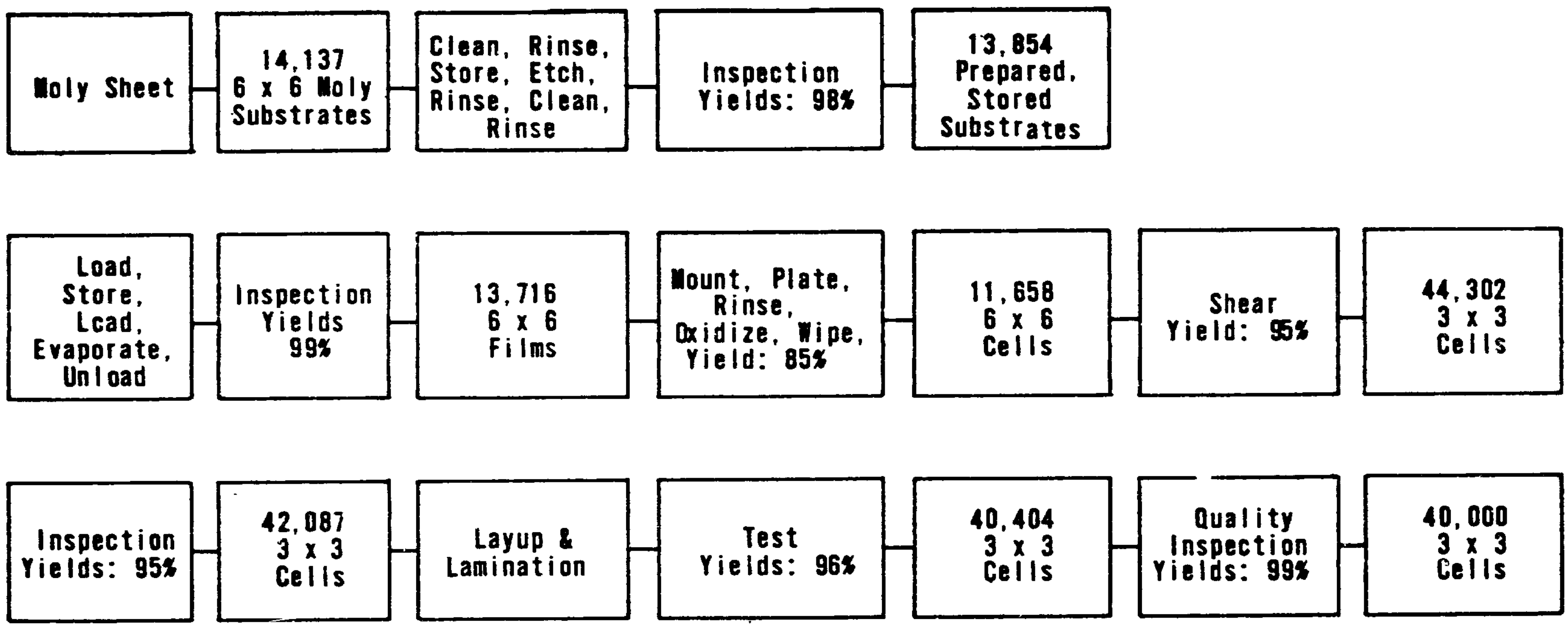


Figure 8

Yield Factors and Cell Quantities for 5 KW/Month

TABLE 3

MANPOWER FOR 5 KW/MONTH

(1) BASED ON ADVANCED 1 KW/MONTH METHODS: (20 DAYS/MONTH)
(24 HOUR/DAY)

Operation	Number /Month (6x6)	Number /Day (6x6)	Time /Unit (minutes)	Time /Month (hours)	Time /Day (hours)
Shear & Trim	14,137	707	.5	118	5.90
Clean	14,137	707	2.	471	28.6
Etch	14,137	707	1.	236	11.8
Load Boats	13,854	693	5.	1,154	57.7
Evap.	13,854	693	5.	1,154	57.7
Mount	13,716	686	.5	114	5.70
Plate	13,716	686	.75	172	8.60
Rinse	13,716	686	1.	229	11.5
Oxidize	12,340	667	.5	103	5.15
Wipe	11,715	586	5.	977	48.9
Shear & Trim	11,658	583	15.	2,915	146.
Inspect & Test	44,302	2,220	2.	1,476	73.8
Leads & Terminals	42,087	2,100	5.	3,510	176.
Layup & Elect.	42,087	2,100	25.	17,550	878.
Lam.	42,087	2,100	5.	3,510	176.
Test	42,087	2,100	1.	702	35.1
Quality Inspection	40,404	2,020	1.	674	33.7
Label	40,000	2,000	1.	667	33.4
Pack & Ship	40,000	2,000	4.	2,667	133.

(2) ADVANCED 5 KW/MONTH METHODS: (20 DAYS/MONTH), (24 HOUR/DAY)

Evap.	13,854	693	.24	55.4	2.77

Other operation times same as above in Section (1).

TABLE 4

EQUIPMENT NEEDS FOR 5 KW/MONTH		ADVANCED UNITS USED ON 1 KW/MONTH		
Item	Type	Unit Cost	No. Required	Total Cost
Metal Shear	Di-Arco No. 3	$ 345	4	$ 1,380
Ultrasonic Cleaner	Westinghouse MT-1	1,200	1	1,200
Evaporators	Five Station	35,000	5	175,000
Thickness Monitor	Federal Products Air Gage	350	1	350
Plating	Harshaw DC Supply	200	1	200
	50-Gal. Plating Tank	200	1	200
	Racks & Holders	50	5	250
Rinsing	Barnstead Transistor Washor TW-50	5,200	1	5,200
Oxidizing	Fries Oven No. 845A	1,475	1	1,475
	Lectrodryer Air Dryer R-6	630	1	630
	Harshaw Pressure Unit, etc.	750	3	2,250
	Tektronix Scope	500	3	1,500
Lamination	Press & Plattens	830	8	6,640
	Welch Vacuum Pump 1402B	255	8	2,040
	Tooling	350	8 sets	2,800
Final Test	Tektronix Scope	500	3	1,500

EQUIPMENT NEEDS FOR 5 KW/MONTH (Same as above except for the evaporators)		ADVANCED UNITS		
Evaporator	Modified NRC 3143	30,000	1	30,000

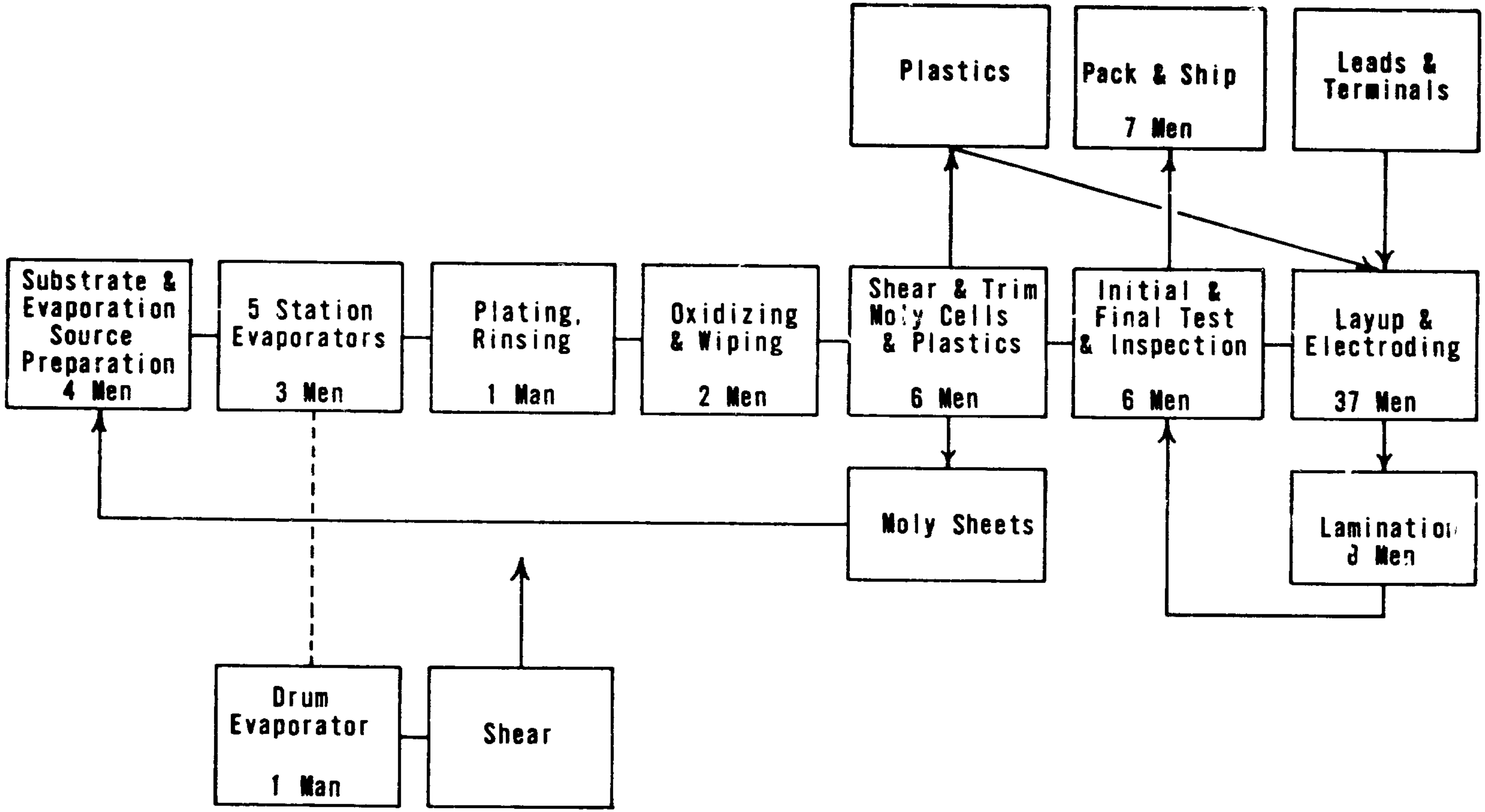


Figure 9

Manpower for 5 KW/Month

Methods similar to those used in production metalling would be the most practical ones for this production rate. A standard horizontal chamber with associated pumps and controls would be used as shown in Fig. 10. The chamber would house a 34 inch diameter cylinder, 58 inches long, on which to mo[illegible] the substrates. Molybdenum strips, the full length of the cylinder, would be held in place by magnetic masks with 6" x 6" apertures. Sixteen strips would be used, giving a total of 144-6 x 6 films per batch. Several evaporation sources would be mounted close to the bottom surface of the cylinder. Pelletized CdS would be used for easy loading of the sources.

During the run, the cylinder would make a complete rotation in 75 minutes. Strip heaters inside the cylinder would preheat the substrates. This process would require approximately 135 minutes per batch giving an average output of 57.5-6 x 6 per hour per unit. Only one unit and one man per shift would be needed.

This method would require some development. The evaporation sources would need the most work. The width of the slit aperture and the temperature would need to be determined experimentally. It might even be necessary to use some type of continuous feed for the cadmium sulfide. With pelletized material, it might be possible to use a gravity feed or a vibration-gravity feed. Something more positive, such as a screw feed, might be necessary. The development effort would be small compared to that required by a semi-automated or automated system. The equipment costs for the proposed system would be less than those for a semi-automated system at this production rate.

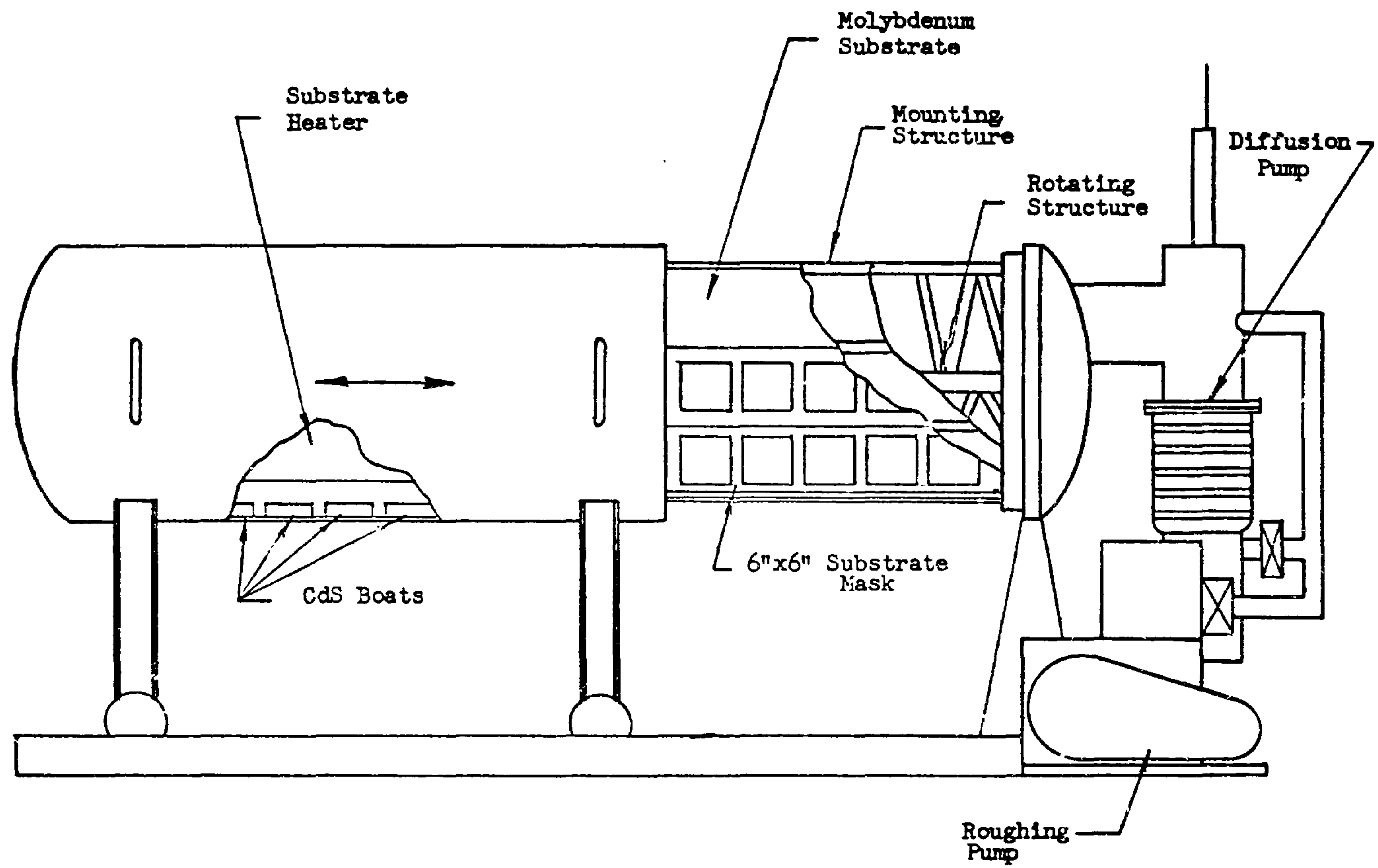


Figure 10

Diagrammic Sketch of Evaporator for Advanced 5 KW/Month

Estimate Of Cost Per Watt For Materials And Labor

COST ESTIMATE FOR MATERIALS OF 3" x 3" CdS SOLAR CELL

Materials	Cost
Molybdenum	$ .53
Cadmium Sulfide	.13
Plastic & Leads	.15
Gold Grid	3.40
Tantalum	.10
Reagents	.74
Total	$5.05

The material costs should be approximately the same for each of the four methods. Next, labor costs are added (exclusive of overhead).

For 1 KW/month by present methods and by advanced methods, 18 process men per shift will be required, at a rate of about $3.24/man hr. Assuming 480 hr./month, this type of labor would require approximately $28,000/month. Three supervisors at $850/man month would be required or $2,550/month. The total labor costs per month would be $30,550/month or $30.55/watt for labor. For 1/8 watt per 3" x 3" cell, as was assumed earlier, materials would cost $40.40 per watt. Labor and materials (exclusive of overhead) would then run $70.95 per watt.

For 5 KW/month, based on advanced 1 KW/month methods, 82 process men per shift will be required for $127,500/month. Three supervisors would again be $2,550/month. Total labor would then be approximately $130,050/month or $27.00/watt for labor. The total labor and materials (exclusive of overhead) would be $67.40 per watt.

The advanced type of equipment eliminates two process men, reducing the labor and materials cost to $65.53. This saving is not large, but 5 KW/month is a logical point at which to switch over to the drum-type evaporator. Only 2.77 man hour of operator time is required in every 24-hour working day. That indicates that the drum-type evaporator could give increased savings at increased production rates.

CONCLUSIONS

This report has outlined four possible courses of action for the early production of thin film cadmium sulfide solar cells. Choice among these possibilities requires consideration of the desired rate of production and urgency of starting date. The four possibilities are as follows:

1. Using present methods and equipment production of cells could start immediately with additional tooling for the increased rate of 1 kilowatt per month. Total equipment cost would be $84,756. Material and labor costs, exclusive of overhead, would be $70.95 per watt.

2. With a minimum development, the proposed five chamber units could be readied for a production rate of 1 kilowatt per month. This advanced system should be more economical than the present one. It would require no changes of critical evaporation parameters. Total equipment cost would be $47,765. Material and labor costs would be the same as in the previous system.

3. Five kilowatts per month should need no more development than 1 kilowatt per month with the five chamber units. Total equipment cost would be $202,615. Material and labor costs, exclusive of overhead, would be $67.40 per watt.

4. With some additional development time, a production type vacuum coater could be put into use for 5 kilowatts per month. The greatest long-run economy could be realized with this advanced system. Even greater economy is possible at higher rates with this system. Total equipment cost would be $57,615. Material and labor costs, exclusive of overhead, would only be $65.53 per watt.

It is urgently recommended that development be started immediately on one of the advanced systems. Which system is chosen is dependent on which rate is desired.

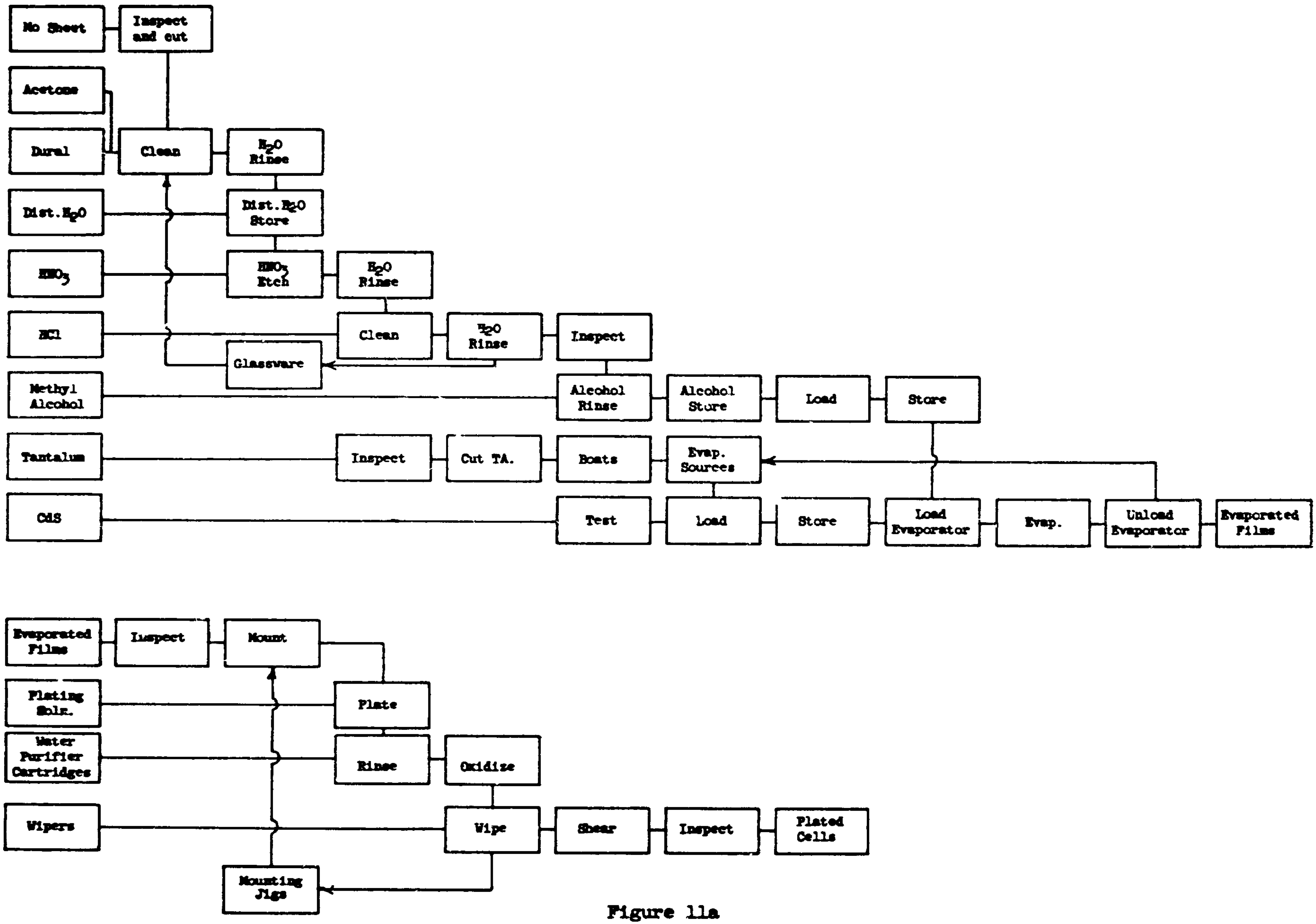


Figure 11a

Production Chart for CdS Solar Cell

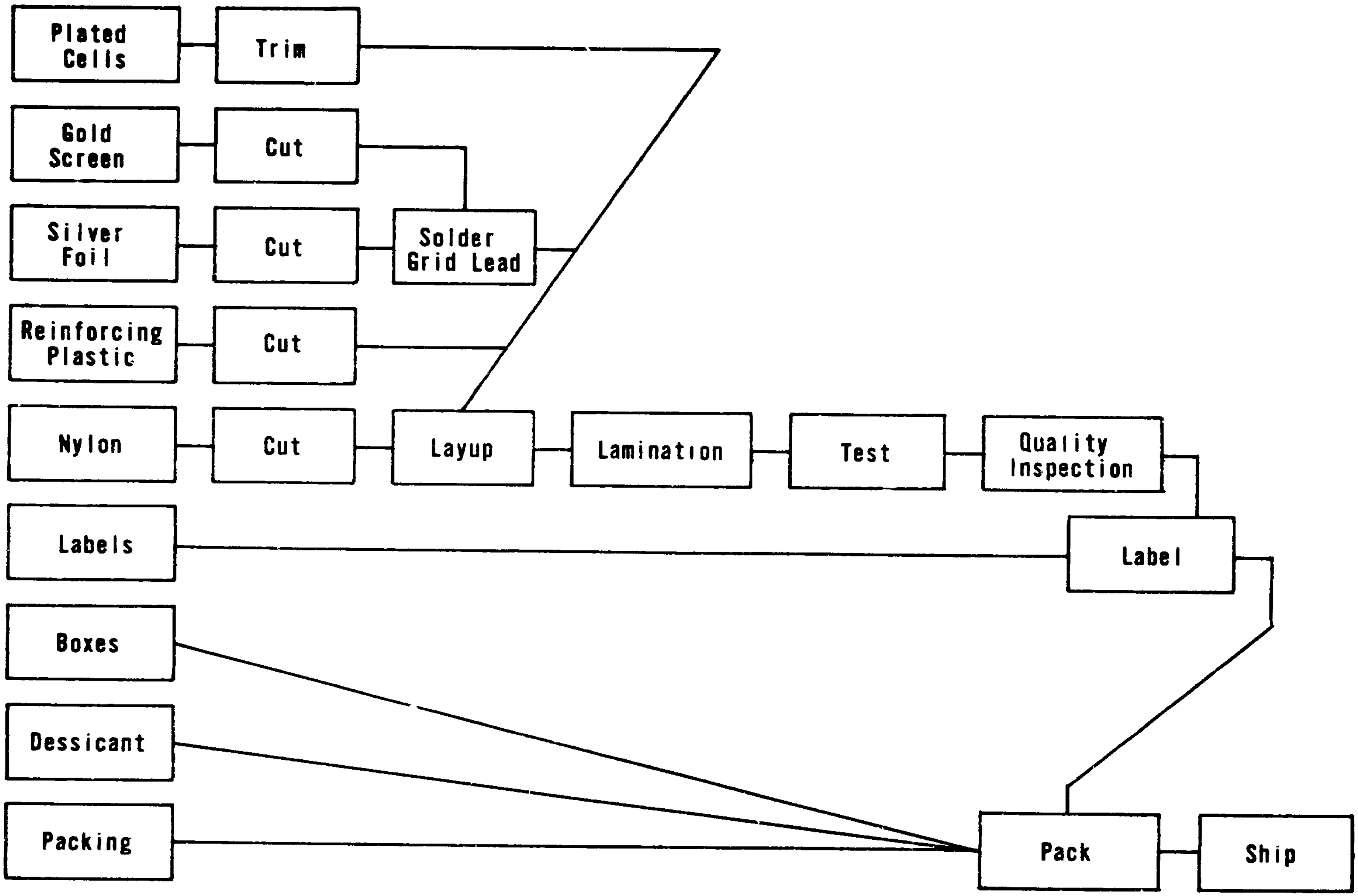


Figure 11b

Production Chart for CdS Solar Cell